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14. ABSTRACT

The goal of this project was to fabricate and measure Silicon spin transport devices designed to uncover the fundamental materials science, device design parameters, and operational limitations including temperature dependence, spin dephasing studies, doping dependence, and spin transport at interfaces. We have made major advancements in understanding the science and engineering of spin transport in silicon in all these aspects, as documented in 5 published research papers, one published review paper, two as-yet unpublished (but publicly-available) manuscripts (one review), and one book chapter.

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FINAL REPORT: N000140910224: Elements of Silicon-based Spintronic Circuits

PI: Ian Appelbaum
Department of Physics
University of Maryland, College Park

Executive Summary

The goal of this project was to fabricate and measure 1. *Vertical* Silicon spin transport devices designed to uncover the fundamental materials science, device design parameters, and operational limitations specific to spin-enabled Silicon-based semiconductor devices, and 2. *Lateral* devices, where the device geometry can be exploited to add further means of spin manipulation and application. This includes temperature dependence, spin dephasing studies, doping dependence, and spin transport at interfaces.

We have made major advancements in understanding the science and engineering of spin transport in silicon in all the aspects listed above through this project. We have developed techniques for injecting and detecting highly spin-polarized electron currents (over 50%), extended the temperature of operation to nearly room temperature (260K),[1] and demonstrated transport of spins over chipscale length (>2 millimeters).[2] In addition, electrostatic gating during lateral spin transport shows the very strong effects of the Si/SiO_2 interface on spin relaxation, indicating a possible route to electrostatic spin control.[3] In those lateral devices, we have also discovered a strong novel magnetocurrent effect.[4] We have shown that the effects of doping on spin relaxation in bulk Silicon are minimal, despite greatly modified device characteristics that were successfully modeled with a Monte-Carlo electron transport scheme.[5] Through temperature studies of spin dephasing and the development of a technique for extracting spin-transport time-of-flight from quasi-static measurements, we have characterized an anomalous spin dephasing mechanism which has currently aroused intense theoretical interest.[6] In ongoing work, we are investigating the use of spin-polarized transport to spectroscopically probe impurity levels.

This progress has been documented in 5 published research papers, one published review paper[7], two as-yet unpublished (but publicly-available) manuscripts (one review), and one book chapter (to appear in a comprehensive handbook).

Personnel supported include postdocs Hyuk-Jae Jang and Yuan Lu in addition to the PI's 1-month effort.

List of Publications Acknowledging Support

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[1] Yuan Lu and Ian Appelbaum, "Reverse Schottky-Asymmetry Spin Current Detectors", Appl. Phys. Lett. **97,** 162501 (2010)

[2] Biqin Huang, Hyuk-Jae Jang, and Ian Appelbaum, "Geometric dephasing-limited Hanle effect in long-distance lateral silicon spin transport devices", Appl. Phys. Lett. **93,** 162508 (2008)

[3] Hyuk-Jae Jang and Ian Appelbaum, "Spin Polarized Electron Transport near the Si/SiO_2 Interface", Phys. Rev. Lett. **103**, 117202 (2009)

[4] Hyuk-Jae Jang and Ian Appelbaum, "Magnetocurrent of ballistically injected electrons in insulating silicon" Appl. Phys. Lett. **97**, 182108 (2010)

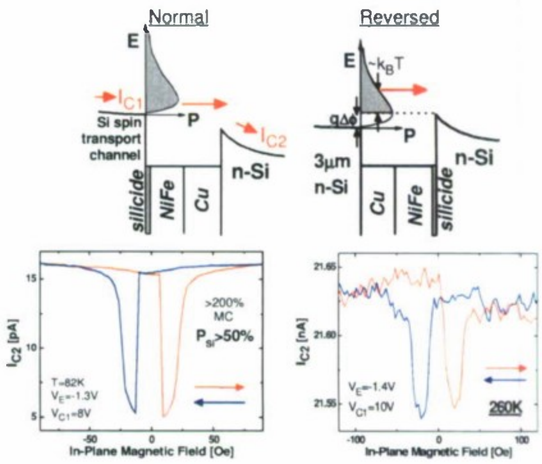
[5] Hyuk-Jae Jang, Jing Xu, Jing Li, Biqin Huang, and Ian Appelbaum, "Non-ohmic spin transport in n-type doped silicon", Phys. Rev. B **78**, 165329 (2008)

[6] Biqin Huang and Ian Appelbaum, "The Larmor clock and anomalous spin dephasing in silicon", arxiv:condmat/1007.0233 (2010)

[7] Ian Appelbaum, "A Haynes-Shockley Experiment for Spin-Polarized Electron Transport in Silicon", Solid-State Electronics **53,** 1242 (2009)

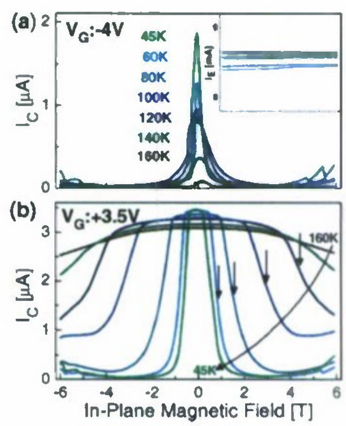
Summaries of published works

Yuan Lu and Ian Appelbaum, "Reverse Schottky-Asymmetry Spin Current Detectors", Appl. Phys. Lett. **97,** 162501 (2010)



By reversing the Schottky barrier-height asymmetry in hot-electron semiconductor-metal-semiconductor ballistic spin filtering spin detectors, we have achieved the following: 1) demonstration of 50% spin polarization in silicon, resulting from the increase of detection efficiency by elimination of the ferromagnet/silicon interface on the transport channel detector contact and 2) evidence of spin transport at temperatures as high as 260 K, enabled by an increase in detector Schottky barrier height.

Hyuk-Jae Jang and Ian Appelbaum, "Magnetocurrent of ballistically injected electrons in insulating silicon" Appl. Phys. Lett. **97,** 182108 (2010):



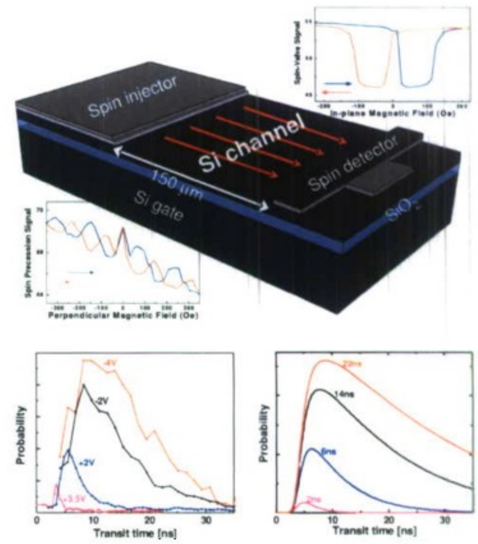
By using ballistic hot-electron injection to achieve lateral conduction through an otherwise fully insulating undoped silicon channel, we are able to study magnetic field suppression of charge transport in a regime normally excluded in Ohmic magnetoresistance measurements. Exceptionally large magnetocurrent changes of >16000% at 45 K in magnetic fields of ~2T are observed, with differential reduction of over 6.2 T^{-1}. Temperature-, electrostatic back-gate-, and magnetic field angle-dependence are presented. This phenomenon is attributed to strong space-charge effects in the dilute three-dimensional electron gas created by nonequilibrium injection.

Ian Appelbaum, "A Haynes-Shockley Experiment for Spin-Polarized Electron Transport in Silicon", Solid-State Electronics **53,** 1242 (2009) [review]:

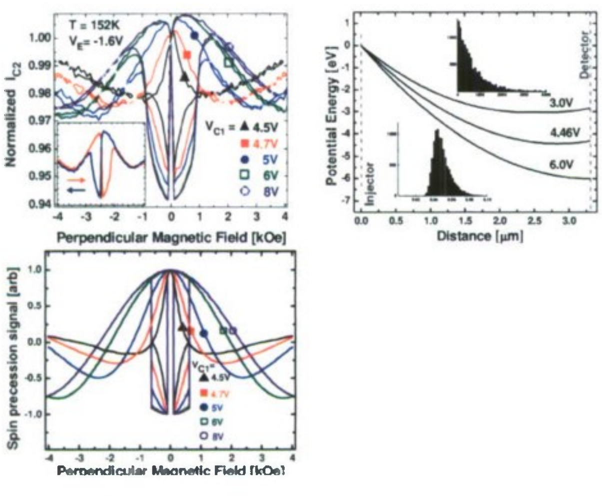
Haynes and Shockley's seminal measurements of minority-carrier transport in semiconductors 60 years ago ushered in a new age of solid-state electronics. However, device scaling issues now compel us to look toward alternative state variables other than charge. Manipulation of electron magnetic moment, or "spin", in semiconductor devices could satisfy this need. The basics of this spin-based technology are discussed and the specific methods necessary for application to silicon are described. Similar to the Haynes–Shockley experiment, we also use a four-terminal device to make fundamental measurements of electron transport parameters that are now sensitive to spin, but without time-of-flight techniques.

Hyuk-Jae Jang and Ian Appelbaum, "Spin Polarized Electron Transport near the Si/SiO_2 Interface", Phys. Rev. Lett. **103**, 117202 (2009)

Using long-distance lateral devices, spin transport near the interface of Si and its native oxide (SiO_2) is studied by spin-valve measurements in an in-plane magnetic field and spin precession measurements in a perpendicular magnetic field at 60 K. As electrons are attracted to the interface by an electrostatic gate, we observe shorter average spin transit times and an increase in spin coherence, despite a reduction in total spin polarization. This behavior, which is in contrast with the expected exponential depolarization seen in bulk transport devices, is explained using a transform method to recover the empirical spin current transittime distribution and a simple two-stage drift-diffusion model. We identify strong interface-induced spin depolarization (reducing the spin lifetime by over 2 orders of magnitude from its bulk transport value) as the consistent cause of these phenomena.



Hyuk-Jae Jang, Jing Xu, Jing Li, Biqin Huang, and Ian Appelbaum, "Non-ohmic spin transport in n-type doped silicon", Phys. Rev. B **78**, 165329 (2008)

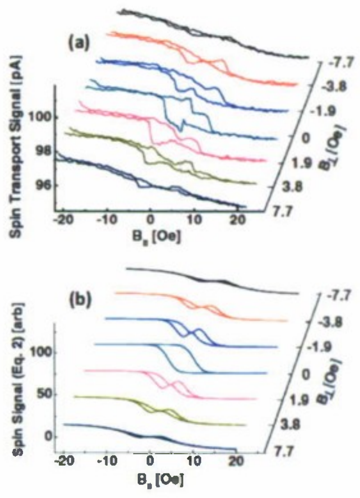


We demonstrate the injection and transport of spin-polarized electrons through n-type doped silicon with in-plane spin valve and perpendicular magnetic-field spin precession and dephasing "Hanle effect" measurements. A voltage applied across the transport layer is used to vary the confinement potential caused by conduction-band bending and to control the dominant transport mechanism between drift and diffusion. By modeling the transport in this device with a Monte Carlo scheme, we simulate the observed spin polarization and Hanle features, showing that the average transit time across the short Si transport layer can be controlled over four orders of magnitude with applied voltage. As a result, this modeling allows inference of a long electron-spin lifetime despite the short transit length.

Biqin Huang, Hyuk-Jae Jang, and Ian Appelbaum, "Geometric dephasing-limited Hanle effect in long-distance lateral silicon spin transport devices", Appl. Phys. Lett. **93**, 162508 (2008)

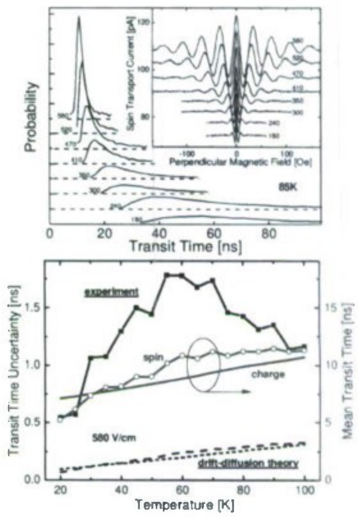
Evidence of spin precession and dephasing "Hanle effect" induced by a magnetic field is the only unequivocal proof of spin-polarized conduction electron transport in semiconductor devices. However, when spin dephasing is very strong, Hanle effect in a uniaxial magnetic field

can be impossible to measure. Using a silicon device with lateral injector-detector separation of over 2 mm and geometrically induced dephasing making spin transport completely incoherent, we show experimentally and theoretically that Hanle effect can still be measured using a two-axis magnetic field.



As-Yet Unpublished Manuscripts:

Biqin Huang and Ian Appelbaum, "The Larmor clock and anomalous spin dephasing in silicon", arxiv:condmat/1007.0233 (2010)



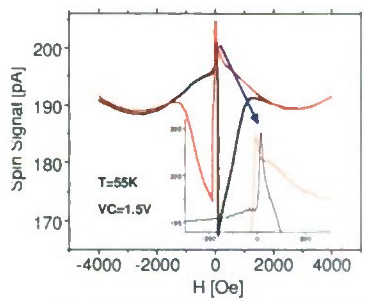
Drift-diffusion theory - which fully describes charge transport in semiconductors - is also universally used to model transport of spin-polarized electrons in the presence of longitudinal electric fields. By transforming spin transit time into spin orientation with precession (a technique called the "Larmor clock") in current-sensing vertical-transport intrinsic Si devices, we show that spin diffusion (and concomitant spin dephasing) can be greatly enhanced with respect to charge diffusion, in direct contrast to predictions of spin Coulomb-drag diffusion suppression.

Ian Appelbaum, "Introduction to Spin-Polarized Ballistic Hot Electron Injection and Detection in Silicon", arxiv:condmat/0910.2606 (2009) [review]:

Ballistic hot electron transport overcomes the well-known problems of conductivity and spin lifetime mismatch that plagues spin injection in semiconductors with ferromagnetic ohmic contacts. Through the spin-dependent mean-free-path, it also provides a means for spin detection after transport. Experimental results using these techniques (consisting of spin precession and spin-valve measurements) with Silicon-based devices reveals the exceptionally long spin lifetime and high spin coherence induced by drift-dominated transport in the semiconductor. An appropriate quantitative model that accurately simulates the device characteristics for both undoped and doped spin transport channels is described; it can be used to determine the spin current velocity, diffusion constant, and spin lifetime, constituting a spin "Haynes-Shockley" experiment without time-of-flight techniques. A perspective on the future of these methods is offered as summary.

Book Chapter:

"Spin-Polarized Ballistic Hot Electron Injection and Detection in Hybrid Metal-Semiconductor Devices", to appear in Spin Transport and Magnetism in Electronic Systems, I. Zutic and E. Tsymbal, eds. (Taylor and Francis)



Other Unpublished Work:

Spin transport through short-channel (3μm) Phosphorus-doped n-type Si devices show voltage-tunable time-of-flight typically in sub-ns range. Precession measurements on these devices therefore have coherent oscillations with magnetic field periods on the 100mT scale. We have recently discovered a strong low-field anomaly at low temperatures which indicates a population of electrons with far longer transit times. Simulation of this data by modeling stochastic capture and emission in shallow traps is ongoing.